MULTIPLE TRANSITIONS IN ROTATING TURBULENT RAYLEIGH-BÉNARD CONVECTION

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Abstract Sharp transitions between potentially different turbulent states are unexpected because one might think that they should be washed out by the prevailing intense fluctuations and short coherence lengths and times. Contrary to this expectation, we found a *sequence* of such transitions in turbulent rotating Rayleigh-Bénard convection as the rotation rate was increased. This phenomenon became most prominent at very large Rayleigh numbers up to 2×10^{12} where the fluctuations are extremely vigorous. It was found in the heat transport as well as in the temperature gradient near the sample center. We conjecture that the transitions are between different large-scale structures which involve changes of symmetry and thus can not be gradual [5, 6, 7].

It has been argued that Kolmogorov's theory of turbulence [4] implies that turbulent flows become featureless when the Reynolds number is large enough (for a discussion of this issue see for instance [2]). Apparently in contradiction to this expectation several experiments recently showed a sharp transition between two different turbulent states [9, 8, 10, 1, 2]. However, all of these investigations were carried out on systems with geometrical constraints in all physical directions, and it is not clear whether the sharp transitions are caused by boundary conditions or whether they would survive in an unconstrained system. Indeed for one of these systems, turbulent rotating Rayleigh-Bénard convection, measurements were made as a function of the lateral extent (aspect ratio) of the system, and it was found that the observed transition moves toward zero rotation rate as the lateral system size approaches infinity [12, 11].

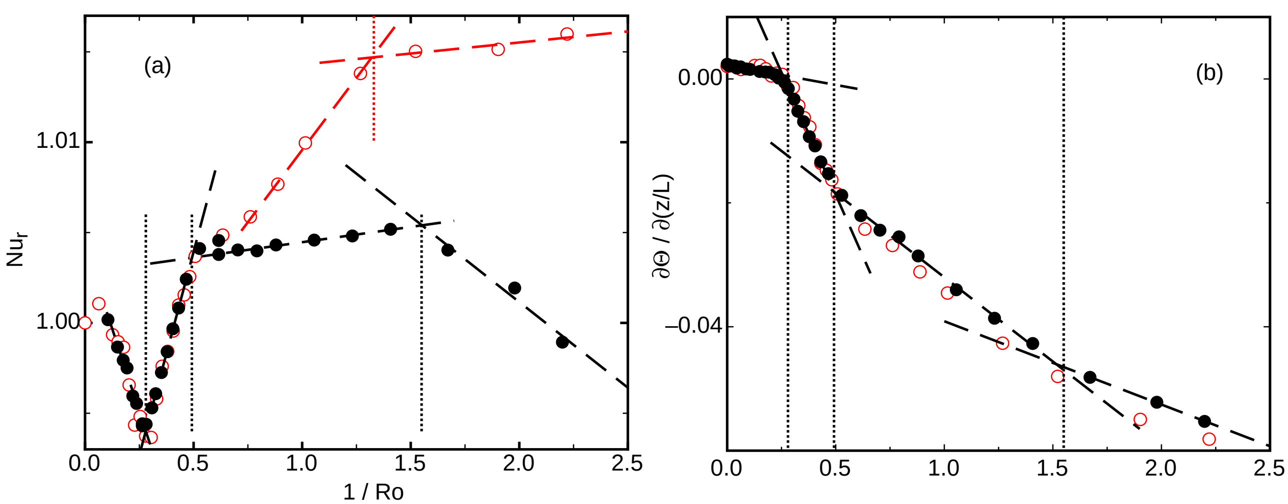

Figure 1. (a): The reduced Nusselt number $Nu_r = Nu(\Omega)/Nu(0)$ as a function of the inverse Rossby number $1/Ro$. (b): The temperature gradient $\partial\Theta/\partial(z/L)$ near the sample center as a function of the inverse Rossby number $1/Ro$. Here Θ is the local time averaged temperature normalized by the applied temperature difference, z is the vertical position, and L is the sample height. Solid symbols: $Ra = 2.07 \times 10^{11}$. Open symbols: $Ra = 1.00 \times 10^{11}$.

Here we report measurements of the heat transport, expressed in terms of the Nusselt number Nu, and of the temperature gradient near the center of a cylindrical sample of fluid heated from below and rotated about its vertical axis at a rate Ω. The Prandtl number was 12.3, and the aspect ratio Γ (diameter over height) was 1.00. The rotation rate is expressed in terms of the inverse Rossby number which is proportional to Ω. Results are shown in Fig. 1. They reveal three sharp continuous transitions. The first, identified as $1/Ro_c$, was found previously for $Pr \simeq 4$ and is associated with the onset of the formation of Ekman vortices which enhance the heat transport by extracting fluid from thermal boundary layers near the plates. It was shown to approach zero as $\Gamma \to \infty$ and thus it is not a feature of the laterally unbounded system. The second and third transitions are found at $1/Ro_{c,2} \simeq 0.492$ and $1/Ro_{c,3} \simeq 1.55$ for $Ra = 2.07 \times 10^{11}$. While $1/Ro_{c,2}$ seems independent of Ra, $1/Ro_{c,3}$ is smaller for smaller Ra.

It seems unlikely to us that all three transitions are characteristic only of the finite system, disappearing as $\Gamma \to \infty$. The detailed origin of these transitions between turbulent states is not known to us, but we presume that it involves a sudden change of large-scale structures of the turbulent flow. Although off hand it seems surprising that a sharp bifurcation should exist in this highly-turbulent state with Ra as large as 2×10^{12} where large-amplitude fluctuations and small coherence lengths might be expected to smooth out any transition between different states, changes of large-scale structures involve symmetry changes. Symmetry-breaking transitions can not be gradual, and instead lead to sharp, albeit possibly continuous, transitions [5, 6, 7]. This is in no way altered by the presence of fluctuations; for if it were, then there also would be no continuous phase transitions (*i.e.* critical points) in equilibrium systems.

Structures at large $1/Ro$ were examined for instance in Ref. [3]. It does not seem clear at this time how these structures correlate with the experimentally observed transitions. However, it is clear for instance that the system can not evolve smoothly from Ekman vortices which are found near the plates and extend only partially into the bulk without correlation between those near the top and the bottom plate to vortex columns which are coherent over the entire sample height and thus reflection symmetric about the horizontal mid plane. The existence of Ekman vortices and of Taylor columns is not restricted to finite systems and should be found as well as $\Gamma \to \infty$.

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